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Very High Speed Holographic Message Routing for Parallel Machines

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Abstract:

An important problem in massively parallel processing machines is the communication bottleneck. For example, in the Connection Machine, a 65,536 SIMD parallel processing message routing is one thousand times slower than the instruction time of an individual processor. This is, in part, due to contention problems and in part to the necessity for global control of the interconnection network. Our approach to solve this problem is to implement a fully-parallel, high-speed message router, using locally-controlled spatial light modulators and volume holograms.
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[Johnson and Reif, 1987] devised an efficient *electro-optical message routing system*. We implemented a small prototype holographic router for demonstration of basic principals. The routing system uses a *volume hologram* to do message switching. It uses *optimal $O(n \log(n))$ number of switches, constant time, and optimal volume*. This work can be applied to do very high speed message routing for *massively parallel machines* such as required by the Connection Machine.

We implemented a small prototype holographic router for demonstration of basic principals. In particular, [Maniloff, Johnson, and Reif, 1989] demonstrated a small working prototype holographic routing system, using $N^{1/2}$ address bits. The small prototype was built in late spring, 1989, to verify the feasibility of this new holographic message routing system. Subcontractor Johnson and Maniloff built this prototype holographic routing system [Maniloff, Johnson, and Reif, 1989] at the Center for Optoelectronic Computing Systems at University of Colorado, Boulder, and Colorado State University. [Strasser, Maniloff, Johnson, and Goggin, 1989] developed a procedure for recording multiple-exposure holograms with equal diffraction efficiency in photorefractive media, which was further refined in 1990.

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Very High Speed Holographic Message Routing for Parallel Machines

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6. Authors of Report: John Reif (Duke), Kristina Johnson (UCB), and Derek Lile (CSU)

7. List of Manuscripts:

"Procedure for recording Multiple-exposure holograms with equal diffraction efficiency in photorefractive media," A.C. Strasser, E.S. Maniloff, K. M. Johnson, and S.D.D.

Goggin, *Optics Letters*, Vol 14, p. 6, Jan 1, 1989 (listed as pre-publication in December 1988 Report).

"Energy Complexity of Optical-Electronic Computations," A. Tyagi and J. Reif, to appear in *Indian Conference on Computer Science,* 1990.

"The Computational Complexity of Optical Beam Tracing," J. Reif, and D. Tygar, Nov. 1989.

"Optical Expanders," A. Tyagi and J. Reif, Aug. 1989.

"Very High Speed Holographic Routing Network for Parallel Processing Machines," E.S. Maniloff, K.M. Johnson, and J. Reif, *EPS/Europtica/SPIE International Congress on Optical Science and Engineering,* Paris, France, April 1989.

"Efficient Algorithms for Optical Computing," A. Tyagi and J. Reif, draft, Dec. 1989.

"Dynamic Holographic Interconnects Using Static Holograms," E.S. Maniloff and K.M. Johnson, in press, *Opt. Eng.,* 1990, (invited paper).

"Maximized Holographic Storage in Photorefractive Lithium Niobate," E.S. Maniloff and K.M. Johnson, submitted, *Appl. Phys. Lett.,* 1989.

"Insulated-gate MQW Optical Modulator on InP/InGaAs," C. Chen, R. Iyer, M. Hafich, G. Lee, G.Y. Robinson, and D. Lile, submitted, *Appl. Phys. Lett.,* 1989.

"InP/InGaAs Based CCD Devices for NOW Spatial-Light Modulator Aplications," K. Han, R. Chang, C. Chen, J. Quigley, M. Hafich, G.Y. Robinson and D.L. Lile, Presented at the Topical Conference on Optical Computing, Salt Lake City, February 1989.

"InP/InGaAs Based CCD Devices for NOW Spatial-Light Modulator Aplications," K. Han,, C. Chen, J. Quigley, M. Hafich, G.Y. Robinson and D.L. Lile, *Proceedings of the First International Conference on InP,* Norman, OK, March 1989.

"Preparation and Characterization of Dielectric Films for Compound and Alloy Semiconductor Field-Effect Devices," *Proceedings of the 6th International Symposium on Passivity,* held in Sappooro, Japan, and to be published in *Solid State Electronics,* September 1989 (invited), (8 Scientific personnel supported by this project).

"Transmission Modulation in InGaAs/InP MOW MIS Diodes," submitted for presentation at the 2nd International InP Conference to be held in Denver, CO, April 1990.

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"A Holographic Network for Parallel Processing Machines", J.H. Reif, E.S. Maniloff, and K. Johnson. EPS/EUROPTICA/SPIE International Congress on Optical Science and Engineering, Paris, France, April 1989.

"Lower bounds on the computational efficiency of optical computing systems", R. Barakat and J Reif, Journal of Applied Optics, Vol 26, p1015-1018, March 15, 1987.

"A Discrete Convolution Algorithm for Matrix Multiplication with Application in Optical Computers", R. Barakat and J. Reif, Journal of Applied Optics, vol 26, p 2707-2711, 1987.

"Holographic Routing Network for Parallel Processing Machines",E.S. Maniloff, K.M. Johnson, and J. Reif, EPS/Europtica/SPIE International Congress on Optical Science and Engineering, Paris, France, April 1989.

"The Computability and Complexity of Optical Beam Tracing", J. Reif, A. Yoshida, and D. Tygar. IEEE Symposium on the Foundations of Computer Science, October, 1990.

"Energy Complexity of Optical Computations", A. Tyagi and J. Reif, Proc of 2nd IEEE Symposium on Parallel and Distributed Processing, Autin Texis, Dec 1990.

"Very High Speed Holographic Message Routing For Parallel Machines", K. Johnson and J. Reif, (funded DARPA proposal) fall 1987.

An Optical Delay Line Memory Model with Efficient Algorithms, A. Tyagi and J. Reif, to appear in Indian Conference on Computer Science , Dec 1990

"Optical Expanders", R. Barakat and J. Reif, June 1990, draft.

"Efficient Parallel Algorithms for Optical Computing with the DFT Primitive", A. Tyagi and J. Reif, submitted for publication, 1990.

"Optical Expanders with Applications in Optical Computing", J. Reif and A. Yoshida, submitted for publication, June, 1990.

"Dynamic holographic interconnects using static holograms", E.S. Maniloff and K.M. Johnson, *Opt. Eng.* **29**, p. 225-229, 1990.

International Topical Meeting on Optical Computing, "Maximized holographic storage in photorefractive lithium niobate", E.S. Maniloff and K.M. Johnson, Optical Computing Conference Record, pg. 191, Kobe, Japan, 1990.

"Limits on photorefractive volume holographic interconnects", E.S. Maniloff and K.M. Johnson, SPIE Technical Symposium on High Power Lasers and Optical Computing, 14-19 January 1990, Los Angeles, CA.

8. *Scientific Personnel supported by this project, institution and degrees awarded during this reporting period:*

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Eric Maniloff, UCB,	C. Chen, CSU
Derek Lile, CSU	Chong-Chang Mao, UCB
Akitoshi Yoshida, Duke	

9. *Outline of Research Findings:*

Summary of Accomplishments:

The problem in massively parallel processing machines is the communication bottleneck. For example, in the Connection Machine, a 65,536 SIMD parallel processing message routing is one thousand times slower than the instruction time of an individual processor. This is, in part, due to contention problems and in part to the necessity for global control of the interconnection network. Our approach to solve this problem is to implement a fully-parallel, high-speed message router, using locally-controlled spatial light modulators and volume holograms.

[Johnson and Reif, 1987] devised an efficient *electro-optical message routing system*. We implemented a small prototype holographic router for demonstration of basic principals.The routing system uses a *volume hologram* to do message switching. It uses *optimal $O(n \log(n))$ number of switches, constant time, and optimal volume*. This work can be applied to do very high speed message routing for *massively parallel machines* such as required by the Connection Machine.

We implemented a small prototype holographic router for demonstration of basic principals. In particular, [Maniloff,Johnson, and Reif, 1989] demonstrated a small working prototype holographic routing system, using $N^{1/2}$ address bits. The small prototype was built in late spring, 1989, to verify the feasibility of this new holographic message routing system. Subcontractor Johnson and Maniloff built this prototype holographic routing system [Maniloff, Johnson, and Reif, 1989] at the Center for Optoelectronic Computing Systems at University of Colorado, Boulder, and Colorado State University. [Strasser, Maniloff, Johnson, and Goggin, 1989] developed a procedure for recording multiple-exposure holograms with equal diffraction efficiency in photorefractive media, which was further refined in 1990.

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Extent of Progress

The work done by the University of Colorado at Boulder includes prototyping a 4-to-4 interconnect network using locally-controlled spatial light modulators addressing photorefractive volume holograms.

A knowledge-based task is to increase the number of holograms, and hence destination addresses that can be stored with equal and maximum diffraction efficiency in photorefractive $LiNbO_3$, a volume holographic recording media.

During this past year, we have succeeded in both constructing and testing the prototype message router, and storing multiple-exposure holograms in volume photorefractive $LiNbO_3$, with equal and maximum diffraction efficiency. These results are described in detail in the journal publication entitled, "Dynamic Holographic Interconnects Using Static Holograms." The reconfiguration rate of the interconnect network is limited by the speed of changing a pattern on the spatial light modulators (SLMs) using ferroelectric liquid crystal. SLMs were purchased from Displaytech, Inc. We can reconfigure the network at a 20 kHz rate. Work is in progress at Colorado State University (CSU) under the direction of Professor Derek Lile to build state-of-the-art SLMs that switch at 6 Gigahertz rates.

This work, described in the journal publication entitled, "Insulated-Gate MQW Optical Modulator on InP/InGaAs," has succeeded in fabricating multiple quantum well modulators with nanosecond response times. This will yield five orders of magnitude increase in routing using the prototype optical architecture.

Applications

This message router has applications to solving the communication bottleneck between parallel processing machines and providing a method for fast access images stored in an optical data base using an associative memory. An address displayed on the SLM performs an associative match with a large database stored in the $LiNbO_3$ crystal. Such an approach could be used by Dr. Stoll at Northrup Corporation to provide parallel access of our 500 images comprised of 220x200 pixels stored in their volume of $LiNbO_3$. Application of fast switching SLMs being developed at CSU include I/O data display, high-speed filtering, correlation and processing, and fast sensors. Future work in this program includes further characterizing a 6-to-6 message router, fabricating an array of InP/InGaAs modulators, and developing a complete model for multiple-exposure holographic storage in photorefractive $LiNbO_3$.

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Reif developed an optical expander system [Reif and Yoshida, 1989] which is used to decrease the number of address bits used by the router (to use only 2 log n address bits per processor) and to improve separation of distinct address patterns matched by the holograms. Computer experiments by consultant Barakat at Harvard verified this optical expander system [Barakat and Reif,1990]. Reif also investigated in 1990 [Reif, Yoshida, 90] how to improve this optical expander system. He has also investigated how it can also be applied to improved holographic storage systems.

Comparison of
Message Routing Systems

Routing Method	Time	Number Switches
Omega Network	$2\log(n)$	$2n \log n$
Crossbar using Matrix-Vector Multiplier	1	n^2
Holographic Message Router without optical expander	1	$n^{1.5}$
Holographic Message Router with optical expander	1	$2n \log n$

Summary of Work Completed and Future Work

Reif has completed tests of the optical expander system via computer experiments both at Duke and with Barakat at Harvard. The availability of a device which can control light with a high spatial resolution and with a short cycle time is critical to the successful realization of a second generation system; therefore subcontractor Derek Lile of Colorado State University has developed improved SLMs. Johnson is planning to build in the future a second generation holographic routing system connecting a larger number of processors using these improvements.

Details of Work at Duke

Optical Expanders

An optical expander is a non-linear electro-optical system which creates N distinct orthogonal boolean patterns, each of size N bits from N distinct input patterns, each of size d bits, where d is no greater than 2 log N. In other words, an optical expander takes as an input a pattern encoded in d bits, and transform it to an expanded pattern as its output which is encoded in N bits. Each output pattern is required to be orthogonal to every other pattern.

More precisely, an optical expander takes as input one of N distinct boolean vectors $p_1, p_2, \ldots, p_N$ of length d, where $d = c \log N$. (Note: c can be about as small as 1.5. However, setting $c = 2$ makes the coding scheme simple, and thus may be preferable in practice.) We call these vectors the {\em input patterns}. Each input pattern is optically encoded by using d pixels, each pixel being either ON (denoted by 1) or OFF (denoted by 0). We will require that each input pattern has exactly $d/2$ pixels ON. The optical expander produces a spatial output pattern r_i from given input pattern p_i. Each output pattern r_i is one of N distinct orthogonal boolean vectors of length N. Furthermore, we assume each output pattern is represented by a coherent light beam—a coherent light beam can address a hologram.

A linear optical system can not be used as an optical expander, since any linear mapping from input of size d creates no more than d linear independent output patterns. Thus, it is impossible to create a set of N distinct orthogonal patterns by any linear optical system.

There are various ways to introduce non-linearity in an optical system. One possibility is to use different coding schemes. In other words, we can apply some linear filtering operations in the spatial frequency domain. After the filtering operations, the coding can be transformed back to the original spatial domain. In coherent optics, spatial fourier transform can be easily implemented by a lens. Another possibility is to use a threshold device. When the intensity of light illuminating a surface is thresholded at a certain level, the thresholded output becomes a non-linear function of the intensity. In this approach, depending on a type of thresholding devices, either coherent or incoherent optics can be used. Our optical expanders use threshold devices to introduce non-linearity.

In the following section (2), we describe applications of our optical expanders. In order to understand the basic idea, we first describe holographic matching in section (2.1), and then in section (2.2) holographic interconnects are discussed. In section (3), we

describe our optical expander in detail. Our optical expander consists of two parts; a linear part and a non-linear part. The linear part is a matrix-vector multiplier, and the non-linear part is an array of thresholding devices. In section (3.1), optical matrix-vector multipliers are discussed. In section(3.2), thresholding operations are discussed.

We describe and investigate an optical system which is called the *optical expander*. An optical expander creates a large number N of distinct orthogonal boolean patterns by use of an electro-optical device with at most d boolean inputs, where $d >= 2 \log N$. We show that an optical expander can not be constructed by using linear optical systems, and so a non-linear optical filter must be used. In our optical expanders, non-linearity is introduced by threshold operations.

Applications of of our optical expanders include a *holographic memory storage system* and a *holographic message routing system*. A holographic memory storage system stores N images, each image indexed by a pattern. These patterns must be orthogonal in order to minimize crosstalk among other images. Our optical expanders produce these N orthogonal patterns with input of d pixels. Thus, with our optical expanders, addressing stored images can be carried out by directly using binary encoded addresses which are sent from the electric interfaces.

Our optical expanders can be used to implement an optical interconnection network, which is capable of dynamically connecting N source units to N destination units in a single step. Without our optical expanders, such an optical network typically requires setting of N^2 individual switches—each source unit must electrically set N switches to connect itself to its destination. In a VLSI system where the wiring is confined on a two dimensional plane, configuring physical wires to set these switches may produce a practical problem for large N. Our optical expanders solve this problem by not actually setting individual N^2 switches, but optically creating a set of spatially modulated patterns which corresponds to setting of N^2 switches. Then, the set of patterns can be used to optically establish connections from N source units to N destination units via holograms.

Thus, our optical expanders are essential in implementing practical optical interconnection networks.

Description of Optical Expanders

An Optical expander is a non-linear electro-optical system which creates N distinct orthogonal boolean patterns, each of size N bits from N distinct input patterns, each of size d bits, where d is no greater than $2 \log N$. In other words, an optical expander takes as an input a pattern encoded in d bits, and transform it to an expanded pattern as its output which is encoded in N bits. Each output pattern is required to be orthogonal to every other pattern.

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More precisely, an optical expander takes as input one of N distinct boolean vectors $p_1, p_2, \ldots, p_N$ of length d, where $d = c \log N$. (Note: c can be about as small as 1.5. However, setting $c = 2$ makes the coding scheme simple, and thus may be preferable in practice.) We call these vectors the *input patterns*. Each input pattern is optically encoded by using d pixels, each pixel being either ON (denoted by 1) or OFF (denoted by 0). We will require that each input pattern has exactly $d/2$ pixels ON. The optical expander produces a spatial output pattern r_i from given input pattern p_i. Each output pattern r_i is one of N distinct orthogonal boolean vectors of length N. Furthermore, we assume each output pattern is represented by a coherent light beam—a coherent light beam can address a hologram.

Optical Expanders require Non-linear optical systems

A linear optical system can not be used as an optical expander, since any linear mapping from input of size d creates no more than d linear independent output patterns. Thus, it is impossible to create a set of N distinct orthogonal patterns by any linear optical system.

Non Linear Optical Filters

There are various ways to introduce non-linearity in an optical system. One possibility is to use different coding schemes. In other words, we can apply some linear filtering operations in the spatial frequency domain. After the filtering operations, the coding can be transformed back to the original spatial domain. In coherent optics, spatial fourier transform can be easily implemented by a lens. Another possibility is to use a threshold device. When the intensity of light illuminating a surface is thresholded at a certain level, the thresholded output becomes a non-linear function of the intensity. In this approach, depending on a type of thresholding devices, either coherent or incoherent optics can be used. Our optical expanders use threshold devices to introduce non-linearity.

Our optical expander consists of two parts; a linear part and a non-linear part. The linear part is a matrix-vector multiplier, and the non-linear part is an array of thresholding devices. See [Reif and Yoshida,90] for details.

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